Clean Energy's Next Revolution

NREL's research accelerates the President's Advanced Energy Initiative

2006 was a banner year for renewable energy and energy efficiency. The wind power industry installed a record 2,700 megawatts of new capacity, while the PV industry now has the capacity to produce more than 1,000 megawatts of solar cells per year and is continuing its rapid expansion. Geothermal energy and concentrating solar power are also experiencing a renaissance.

Renewable fuels grew at a record pace, as well; the ethanol fuel industry produced about 5 billion gallons of ethanol, an increase of about 28% in just one year, while new projects are expected to double that capacity by mid-2008. Likewise, U.S. production of biodiesel tripled to 250 million gallons, and enough biodiesel production facilities were operating by year's end to more than double that production level.

Energy-efficient technologies also posted significant gains in 2006, and with President George W. Bush's declaration that "America is addicted to oil," the greatest emphasis was on hybrid electric vehicles. Thanks in part to state and federal tax credits, roughly 130,000 hybrid vehicles were sold in the United States. Automakers also started rolling out vehicles with efficient six-speed transmissions, lighter engine components, and other fuel-efficient innovations.

However, these impressive gains were accompanied by signs that some clean energy technologies are reaching limits in their rates of growth. Constraints in the supply of silicon held back growth in the PV industry, and despite the industry's rapid growth, some experts predict that the demand for solar cells will significantly exceed the supply through the end of this decade. Likewise, the expanded ethanol fuel industry is expected to consume 20% of next year's corn production, an outlook that contributed to a boost in corn prices near the end of 2006. Despite the growing number of hybrid vehicles on the road, U.S. petroleum consumption is expected to continue increasing for the foreseeable future.

Looking toward the future, President Bush unveiled his Advanced Energy Initiative (AEI) during the 2006 State of the Union Address. The AEI aims to change the ways in which we fuel our vehicles and power our homes and businesses by accelerating our use of five renewable energy and energy efficiency technologies: advanced batteries, cellulosic ethanol, hydrogen, solar power, and wind power.

Advanced lithium-ion batteries would help to commercialize plug-in hybrid vehicles, which can be charged from a home power outlet and can run on all-electric power for up to 40 miles. This would allow most people to use little or no gasoline during commutes to and from work and limit their gasoline use on longer trips, providing an opportunity to significantly reduce the nation's petroleum usage. Cellulosic ethanol draws on nonfood sources of biomass, such as trees, grasses, and agricultural wastes, and allows a large expansion in the production of ethanol fuel. And hydrogen vehicles present an opportunity to create a new hydrogen economy, which can be powered in part by renewable energy.

To advance solar energy technologies, the President launched the Solar America Initiative, which aims to make solar PV technologies cost-competitive with other forms of renewable electricity by 2015. And to boost the deployment of wind power throughout the country, the AEI emphasizes the development of new small-scale wind technologies to power homes and businesses in areas with low wind speeds.

This special section of the NREL Research Review examines how NREL is supporting the president's initiatives through innovative research. NREL's emphasis on translational science—scientific research conducted with industry goals in mind—is yielding significant advances in lithium-ion battery technologies, cellulosic ethanol, hydrogen production from sunlight, small wind turbines that capture low-speed winds, and new low-cost, high-efficiency solar cells. Through the research efforts highlighted here, plus many other related and ongoing efforts, NREL's research is truly enabling the next clean energy revolution. ■

Advanced Batteries

Nanotechnology Promises Capacity Boost for Lithium-Ion Batteries

An NREL-funded effort to create metal oxide nanomaterials could significantly boost the capacity of today's lithium-ion batteries, the leading contender in next-generation battery technology for plug-in hybrid vehicles.

"With these new nanostructured materials, we've come close to achieving an energy storage capacity that is double the capacity of graphite, which is the commercially employed anode material," says NREL Scientist Anne Dillon. "Furthermore, no degradation has been observed upon significant laboratory testing, indicating the films are very durable."

Nanostructured materials, or nanomaterials, consist of particles on the scale of a billionth of a meter (a nanometer)—hence the name. Dillon has been working with NREL Scientists Se-Hee Lee and Harv Mahan to make anodes for lithium-ion batteries using nanoparticles of molybdenum oxide. Over the past three years, the project has been funded through NREL discretionary funds, known as Laboratory Directed Research and Development funds.

The process starts with hot-wire chemical vapor deposition (CVD), a technique originally pioneered by NREL to deposit amorphous silicon films for solar cells, and subsequently adapted to deposit carbon nanotubes for a variety of applications. In this current adaptation of hot-wire CVD, a molybdenum filament is heated to a white-hot temperature, about 2000°C, inside a quartz tube filled mostly with argon, an inert gas.

Introducing a small amount of oxygen causes the surface of the filament to evaporate, resulting in nanoparticles of molybdenum oxide, which form in the gas phase and condense on the quartz surface as a powder. Once removed, this powder can then be suspended in a methanol solution, and when a voltage is applied to it, it will deposit in thin, porous films.

Because the oxide films are actually made of millions of tiny particles, they have a high surface area, which allows them to act extremely efficiently as an anode, or negative terminal, of a lithium-ion battery. The team plans to apply a similar approach to the battery's positive terminal, or cathode.

"We're going to develop other metal oxide materials for cathodes and hope to get a similar improvement in capacity," says Dillon.

One advantage of the nanoparticle terminals is their sponge-like texture, which allows them to easily expand and contract. That creates the potential to build a solid-state lithium-ion battery, replacing the battery's liquid electrolyte with a polymer.

As that polymer expands and contracts with temperature, the nanoparticle terminals could flex along with it; graphite, in contrast, is relatively brittle. The goal is to increase not only the energy capacity of the battery, but also the speed at which it can produce electricity, a factor known as its rate capability.

"If lithium-ion batteries are ever going to be used for plug-in hybrids, you need to improve the rate capability, and our nanostructured materials have shown a better rate," says Dillon. ■

NREL Scientist Anne Dillon examines the hot-wire chemical deposition system, which produces metal oxide nanoparticles for use in lithium-ion batteries.

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NREL researchers often employ molecular beam epitaxy to build multi-junction solar cells. Within the vacuum chamber shown here, solar cell materials are heated until they begin to evaporate. They are then condensed onto a substrate in a controlled process, resulting in ordered crystalline layers of semiconductor materials.

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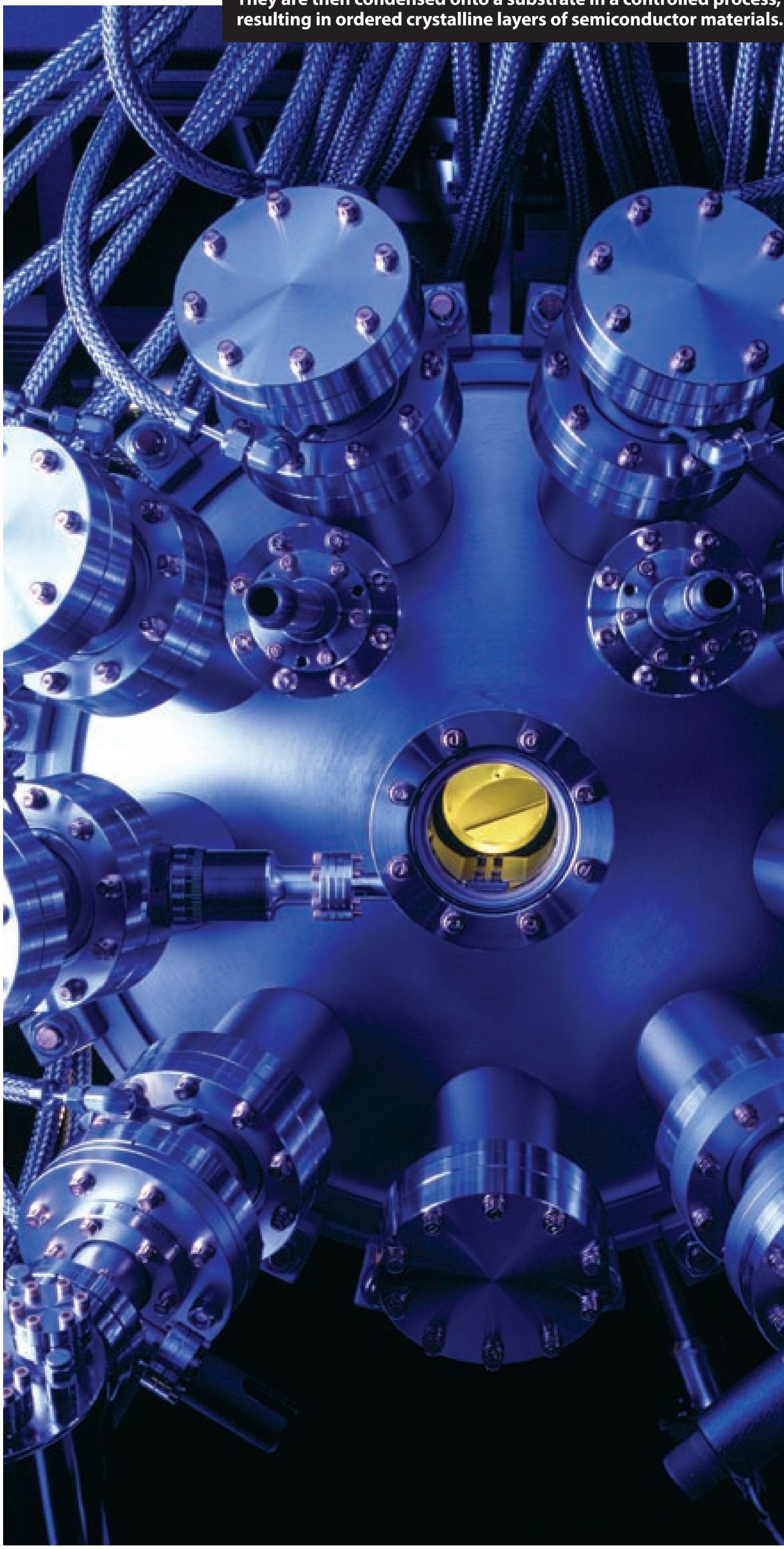


Solar Power

NREL Shoots for the Sun with New Photovoltaic Technologies

NREL is aiming for new solar power technologies that will significantly reduce the cost of solar electricity. What those technologies will be is anyone's guess, but the odds are good that NREL will have a hand in them.

"Some people think the thin-film approach is going to be 'the thing' of the future," says Researcher Supervisor Sarah Kurtz, "while others see great promise in organic solar cells and nanotechnologies. Meanwhile, researchers developing thinner silicon solar cells say 'don't bet against silicon,' because silicon is always the king. And other people are saying the concentrator approach has real potential."

The Concentrator Approach: A 40%-Efficient Solar Cell

Kurtz is likely part of that latter group, because she and Scientist Jerry Olson played a key role in developing multijunction solar cells, which have now achieved a 40% conversion efficiency. In other words, 40% of the sunlight hitting the solar cell is converted into electricity. The achievement by Spectrolab, a Boeing Company subsidiary, involved concentrating sunlight onto a triple-junction solar cell, which produced a world-record efficiency of 40.7%.

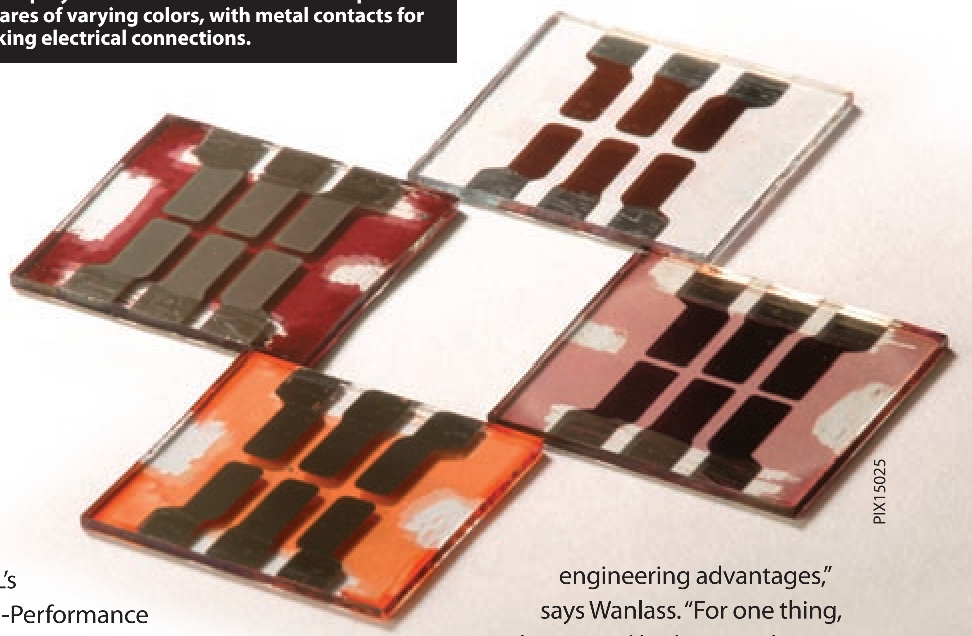
Such solar cells are much more expensive than today's silicon solar cells, but their high efficiency can help to offset the high cost. The cells use sunlight that is concentrated by mirrors or a plastic Fresnel lens, a design that requires a tracking device to keep the solar concentrators pointed toward the sun. For such concentrating solar cells, the level of concentration is generally referred to as the number of suns: "100 suns" is sunlight concentrated 100-fold. While the tracking device adds to the cost, a 100-sun concentrator only needs one square centimeter of solar cell material for every 100 square centimeters of collector area.

Through a combination of basic and applied research into the properties of semiconductor materials and devices, Kurtz and Olson advanced the concept of the two-junction solar cell—which places two layers of PV material atop one another—by developing a high-efficiency cell and bringing it to commercialization. With NREL's participation, Spectrolab and others extended that concept to a triple-junction cell, which consists of three layers of PV material. Each of the three materials captures a separate portion of the solar spectrum—this is known as the material's bandgap—and the aim is to capture as much of the solar spectrum in the three layers as possible. But that's not easy.

Traditionally, one difficulty in picking materials with the right bandgap is that the separate layers should also have similar crystal structures, in which the atoms are spaced the same distance apart. That equal lattice constant keeps the solar cell from suffering from fatal defects and poor bonds when the crystals don't line up well with each other in the interface between the layers. Unfortunately, limiting the solar cells to materials with the same lattice constant ultimately limits their efficiency.

A relatively new approach is the metamorphic or mismatched lattice solar cell, which combines materials with different lattice constants. To avoid problems with defects and poor bonding, these solar cells employ an inactive transitional layer that gradually shifts from one lattice constant to another. The transition is made by steadily changing the percentage of one material in the transitional layer as it is grown. Working under NREL's High-Performance Photovoltaic Program, Spectrolab used this approach to create its record-breaking cell.

NREL's polymer solar cells consist of small plastic squares of varying colors, with metal contacts for making electrical connections.



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"The real challenge," says Kurtz, "is to implement those bandgaps in a monolithic structure that's grown continuously, step-by-step, with materials of near perfect quality. You have to control thousands of little details all at once to hit that champion efficiency."

Metamorphic materials can be used in a wide variety of cell configurations, such as in the inverted solar cell approach that has been studied by both NREL and Spectrolab. In this approach, the cell is built upside down, laying down the top layer first on a substrate and adding the bottom layer last. The solar cell is then removed from the substrate it was grown on and can be applied to a material of choice. NREL Scientist Mark Wanlass was one of the first researchers to achieve high efficiencies in an inverted solar cell, as described in detail in the 2005 NREL Research Review. NREL's solar cell has already achieved an efficiency of 37.9% at 10 suns, but computer models suggest the cell, once perfected, could achieve an efficiency of 43% or higher at 500 suns.

"The inverted cell has a higher performance potential, and excellent cost and engineering advantages," says Wanlass. "For one thing, the original high-cost substrate is removed and can be reused, and the resulting ultra-thin tandem cell can be mounted on a desired supporting substrate. The supporting substrate can be engineered to address the needs of a particular application, such as flexible, ultra-lightweight cells for space, or robust, thermally conductive cells for terrestrial concentrators."

Meanwhile, NREL is working to develop a 50%-efficient cell, a goal that Kurtz sees as achievable.

"The ways to get closer to 50% are twofold," says Kurtz. "One way is to adjust the bandgap choices to come closer to optimal values, while still retaining very high perfection in the materials. The second approach is to add more junctions—again, with optimally chosen bandgaps—while maintaining perfection in the materials."

The Low-Cost Approach: Plastic, Nanotechnology, and Printed Solar Cells

While Kurtz, Olson, and Wanlass pursue the high-efficiency route, another group of NREL researchers are taking the opposite approach: produce a solar cell as cheaply as possible, because even if it has a low conversion efficiency, it will still

PIX15024

William Rance, a graduate student at the Colorado School of Mines, inserts a tray of polymer solar cells into a high-vacuum deposition chamber, where metal contacts are deposited onto the solar cells.

be a low-cost way to produce electricity.

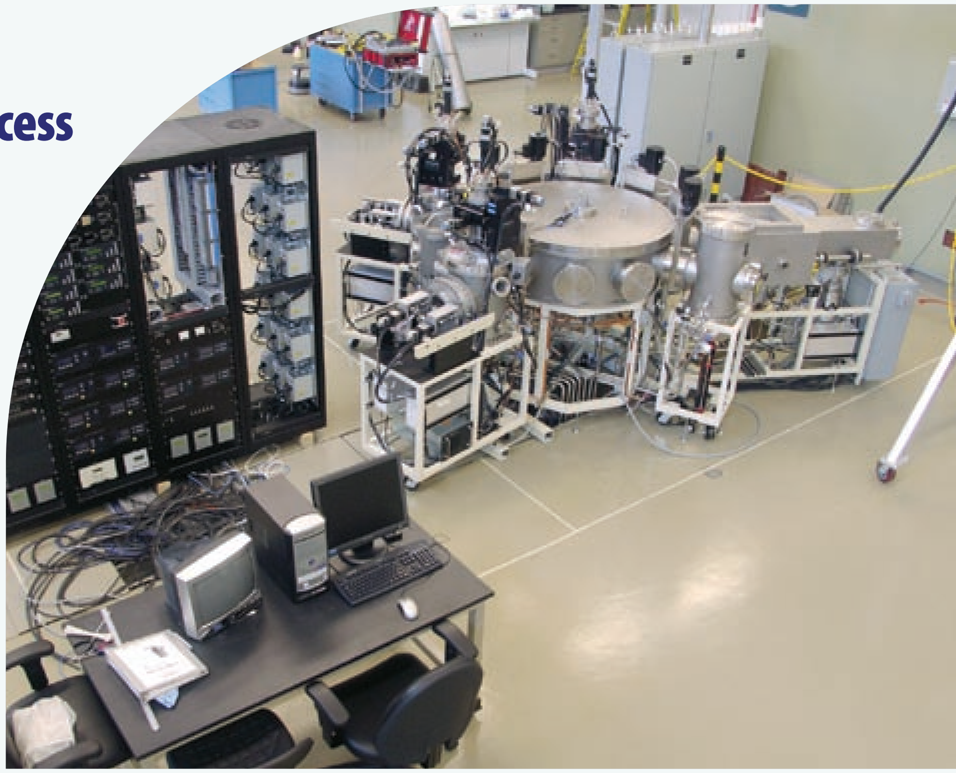
Scientist Sean Shaheen is leading an NREL effort to produce inexpensive solar cells made from plastics that can conduct electricity. These organic solar cells function differently than standard solar cells do, generating an exciton—a bound pair of an electron and a positively charged hole—that migrates to a nearby boundary and then separates, yielding free charges than can produce electrical current. Excitons won't migrate far, though, so these organic solar cells require the engineering of structures with features that are typically on the order of only tens of nanometers (billionths of a meter) thick.

NREL has been working with Konarka Technologies to create inexpensive plastic solar cells with conversion efficiencies exceeding 5%, which is high for plastic solar cells. The trick is to incorporate small nanometer-sized particles into the plastic. So-called buckyballs or fullerenes—nanoscale soccer balls made of carbon atoms—act as sites where excitons can separate into charge carriers.

NREL researchers are also investigating a number of analogous approaches to increasing the efficiency of plastic solar cells, such as embedding the polymer in a porous semiconductor film, impregnating the polymer with nanofibers of zinc oxide, or using polymers that branch out in a tree-like shape, called dendrimers.

Another way to cut solar cell costs is to fabricate them quickly and cheaply. Research Supervisor David Ginley has been working with HelioVolt Corporation to adapt ink-jet printing techniques to quickly deposit thin films of copper indium gallium selenide, a strong contender among thin-film solar cells. NREL has also employed ink jet printers to quickly apply metallic contacts to a range of solar cell materials. ■

NREL Launches Process Development and Integration Laboratory



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The silicon cluster tool, which allows for robotic manipulation of silicon solar cells in a vacuum environment, was the first addition to the new PDIL.

It's all about the vacuum. The 11,400-square-foot Process Development and Integration Laboratory (PDIL) in NREL's new Science and Technology Facility is a masterpiece in vacuum technology, featuring a variety of vacuum chambers and robotic sample handlers that keep thin-film solar cell samples isolated not only from dust but also from oxygen and other reactants in the air.

"Once the sample is initially introduced to the vacuum, it never sees air again until you're done with it," says NREL Scientist Brent Nelson, the process integration project leader.

Although the laboratory equipment is just starting to arrive in the massive laboratory space, one instrument completed in late 2006 and slated to arrive at NREL in early 2007 is indicative of the vision for the PDIL. Called the silicon cluster tool, it features a central vacuum robot that shuttles samples between eight surrounding vacuum chambers, where layers of silicon and transparent zinc oxides can be applied, as well as etching and passivation treatments. Scientist Qi Wang in NREL's Silicon Group will be the principal operator for the tool, which will be used to fabricate amorphous silicon solar cells and to passivate silicon wafers in support of thin crystalline-silicon solar cells.

The cluster tool features several combinatorial chambers that will allow researchers to lay down 10 strips of material with different properties in both the horizontal and vertical directions, resulting in a 10-by-10 grid that provides 100 different combinations on one 6-inch-by-6-inch sample. Those chambers allow researchers to more quickly explore different parameters to find the optimal combinations, an approach often referred to as high-throughput research.

At any point in the process, a vacuum chamber containing a sample can be wheeled away to an analytical instrument or even to an entirely different cluster tool. Only a handful of places in the world employ such inter-tool transport while maintaining a vacuum in the chamber, and most of those are for small samples; NREL may be the only place in the world employing such tool integration with such large samples. The vacuum chambers made it unnecessary to build a clean room, which in turn would have made the PDIL a much more expensive facility. They also allow several different thin-film technologies to share one set of expensive analytical tools.

The idea is actually borrowed from the semiconductor industry, in which plastic boxes containing clean dry air are used to transfer semiconductor samples without exposing them to dust particles. The PDIL just takes the concept a step further by protecting samples from molecular level contamination; vastly reducing material reaction with molecules found in the air, such as water vapor and oxygen. The concept was first championed by NREL Group Manager Peter Sheldon in a technical paper published back in 2000.

The first cluster tool to be installed in the PDIL is for amorphous and crystalline silicon solar cells. However, the build-out plan for the laboratory includes characterization tools and similar cluster tools for solar cells made from cadmium telluride, copper indium diselenide, polymers, and nanomaterials. ■

Cellulosic Ethanol

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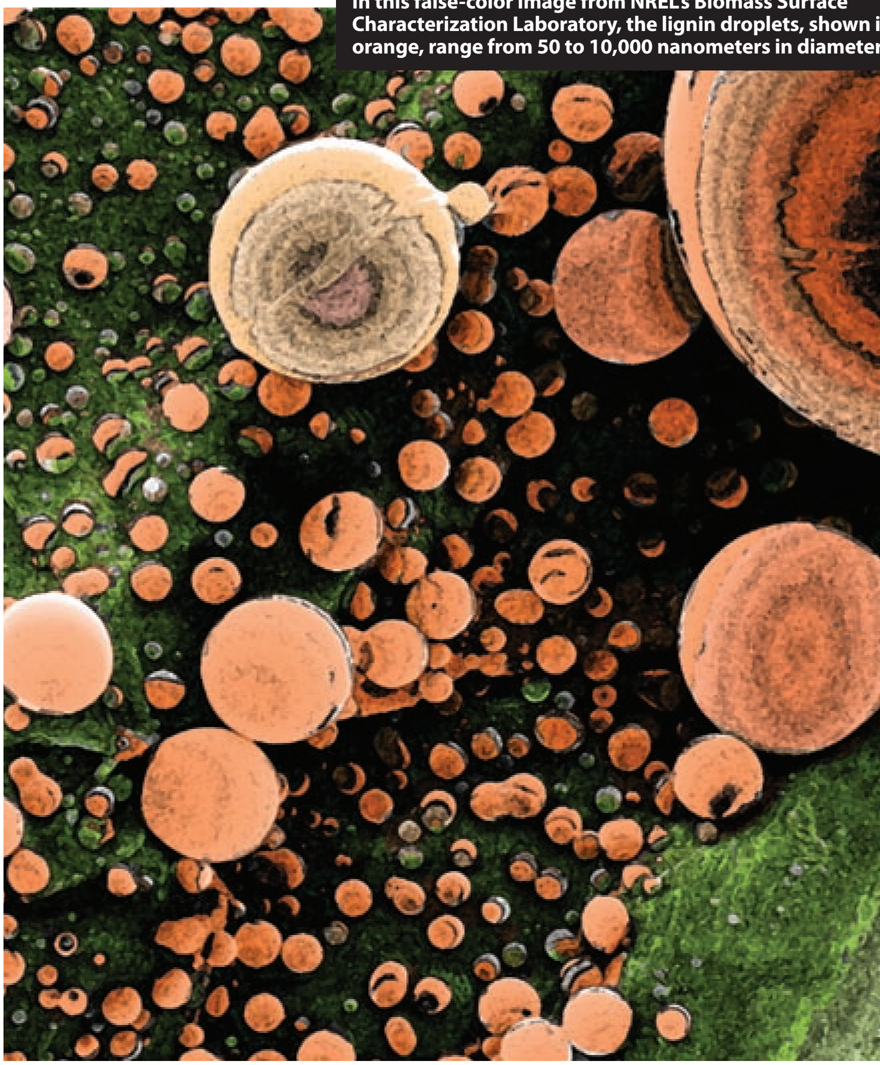

The thermal pretreatment of lignocellulosic biomass disperses the glue-like lignin into droplets of varying sizes. In this false-color image from NREL's Biomass Surface Characterization Laboratory, the lignin droplets, shown in orange, range from 50 to 10,000 nanometers in diameter.

NREL Laboratory Aims to Break Down Nature's Defenses

Plants have evolved to be able to defend themselves against a wide variety of insect, fungal, and bacterial attackers. Although the attacking armies come equipped with a variety of enzymes that try to weaken a plant's defenses, the plants have quite a few tricks of their own up their sleeves.

Grasses and tree barks, for instance, have an outside rind consisting of a waxy barrier and densely packed cells. The plants' cell walls are made of highly crystalline cellulose, a material generally resistant to enzymes, and a coating of hemicellulose and lignin, which protects the cellulose from microbes. While cellulose and hemicellulose are both carbohydrates, lignin is a water-resistant polymer that also helps form the vascular channels within the plant.

All these components work together to form a strong defense for grasses, trees, and the inedible parts of agricultural crops, which scientists refer to as lignocellulosic biomass. But these same defenses make it difficult to free the sugars from within the biomass and allow them to be converted to fuels such as ethanol.

Scientists refer to the resistance of lignocellulosic biomass to being broken down as biomass recalcitrance. NREL and its industrial partners have discovered ways to get past plants' defenses, for instance, by using heat, pressure, and dilute acid to break down hemicellulose into its component sugars. A cocktail of three enzymes can then convert the cellulose into glucose molecules, in a process known as hydrolysis.

Despite these approaches, the general problem of recalcitrance of the plants has not been overcome. For instance, two batches of cornstalks and leaves might appear the same, but will react much differently to such acid pretreatments and hydrolysis steps. Clearly, a greater understanding of the structure of these plants is needed to understand what makes some plants more resistant to chemicals and enzymes than others.

To address these issues, NREL has launched the new Biomass Surface Characterization Laboratory (BSCL). The BSCL is well equipped with imaging tools to help NREL scientists understand the structure of plants. The instruments include a scanning electron microscope for high-power images; an atomic force microscope to study cell wall surfaces; a transmission electron microscope to reveal internal structures and their chemistry; a near-field scanning optical microscope, which can perform spectroscopic analysis of surfaces and focus on single molecules; and a confocal microscope, which can yield three-dimensional images of samples.

Launched in 2005, the BSCL has already yielded insights into biomass recalcitrance. By studying the pretreatment processes used to break down the hemicellulose and remove the lignin, the BSCL revealed that some of the hemicellulose is converted directly into sugars, while the hemicellulose that is linked to lignin is carried into the solution. That means that, for plants in which most of the hemicellulose is linked to lignin, a low percentage of that hemicellulose will be broken down into sugar, so less fuel will ultimately be generated from the biomass.

NREL is also attacking the problem from a different angle, trying to better understand the enzymes that break down cellulose. Called cellulases, the enzyme complexes actually consist of a collection of protein enzymes, and each one plays a role in breaking down cellulose to glucose molecules.

To understand how cellulases work, NREL is employing CHARMM (Chemistry at Harvard Molecular Mechanics), a software model for simulating the actions of large molecules. The NREL simulations include roughly one million atoms to model the enzyme, the cellulose, and the surrounding water simultaneously. If that's not enough, NREL needs to run the model for 25 million steps that will equal 50 billionths of a second, making it the largest biological computer model yet attempted.

To extend the CHARMM model to such a huge problem, NREL researchers and their partners at the Colorado School of Mines and Cornell University have teamed up with software developers at The Scripps Research Institute and with computational scientists at the San Diego Supercomputer Center at the University of California, San Diego. One solution is to run parts of the CHARMM model in parallel to speed the computations.

The computer model is expected to answer questions about how the cellulase enzyme complex interacts with cellulose; one such question is whether the enzyme acts on only one face of the cellulose crystal. Water is also an important part of the equation, because it forms a high-density layer on the surface of cellulose. Understanding how the cellulase complex disrupts that water layer may be key to understanding its function. ■

Hydrogen

Cellular "Factories" Aid Search for Key to Converting Sunlight to Hydrogen

NREL Scientist Maria Ghirardi has billions of factories churning out their products in support of her research. Her helpers are very small, though: they are tiny cellular factories of E. coli bacterium, busily manufacturing the hydrogenase enzyme that could be the key to producing hydrogen from sunlight. Such a process could one day provide a renewable energy source for fueling future hydrogen vehicles.

Scientists have long known that under some conditions, the green alga Chlamydomonas reinhardtii would produce hydrogen. The enzyme at the heart of this hydrogen-producing process is called hydrogenase, and it has a unique ability to combine protons and electrons to form a hydrogen molecule. Because photosynthesis—the process that plants use to convert sunlight to chemical energy—also generates a lot of electrons, scientists see a potential for combining photosynthesis with hydrogenases to generate hydrogen from sunlight.

But there's a big problem: photosynthesis also generates oxygen, and most hydrogenases can't tolerate oxygen. So the key to the process is to find a hydrogenase enzyme that tolerates oxygen and is still very active, churning out lots of hydrogen.

Back in 2000, Ghirardi and NREL Research Fellow Mike Seibert joined researchers from the University of California, Berkeley, to announce that they had found the key to forcing Chlamydomonas to produce the energy-rich gas: they deprived it of sulfur. This approach—based on an understanding of the alga's metabolism garnered through years of research—decreased the alga's internal production of oxygen and caused it to consume any oxygen produced by photosynthesis.

In the absence of net oxygen, the alga reverted to an alternate metabolic pathway, which generated hydrogen through the degradation of starch and through the photosynthetic oxidation of water. The process works, but the photosynthetic process yielded low amounts of hydrogen. In order to fully utilize the available sunlight for hydrogen production, the research team realized that they needed to find or engineer a hydrogenase that functions well in the presence of oxygen.

"There are a few hydrogenases in nature that are more tolerant to oxygen, but they're not found, so far, in photosynthetic organisms," says Ghirardi. "Why is that important? Because in photosynthetic organisms, you can get hydrogen directly from water, and in non-photosynthetic organisms, you have to feed them some carbon source, so it's not as economically desirable."

A major problem that NREL researchers faced was the lack of a simple way to study and engineer algal hydrogenases. The hydrogenase consists of a metallic catalytic cluster bound to a protein structure, and earlier attempts to insert the hydrogenase genes into E. coli, an organism commonly used for such purposes, yielded inactive enzymes that lacked the critical metallic cluster.

That all changed in 2005, when Ghirardi and Research Associate Matthew Posewitz were studying the green alga Chlamydomonas by creating random mutations in its genome. Using a process called insertional mutagenesis, the researchers inserted pieces of DNA at random on the alga's genome to disrupt genes.

"We looked for the mutants that could not produce hydrogen, and among the ones that we found was this particular

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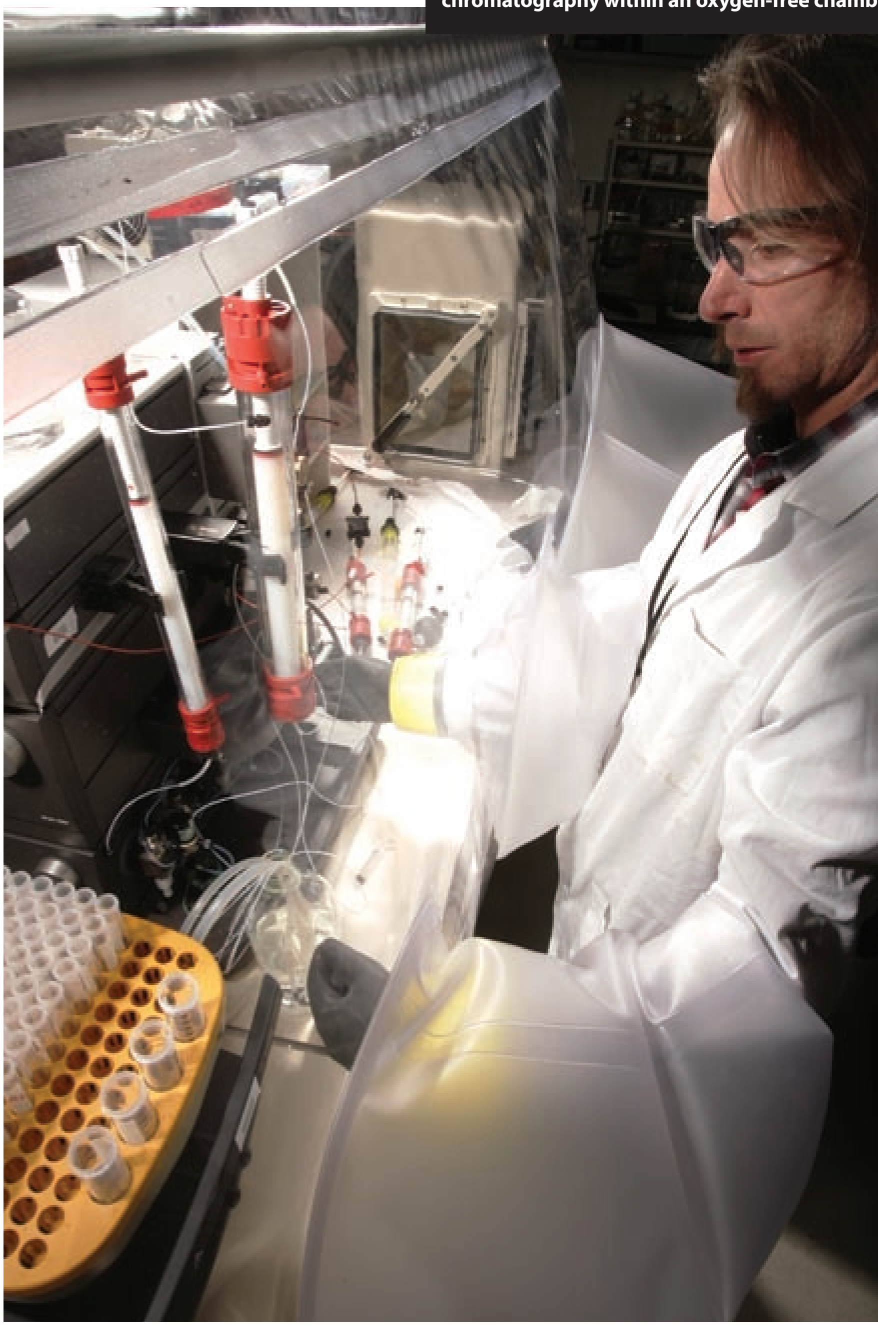
Paul King purifies biological catalysts for hydrogen production using fast protein liquid chromatography within an oxygen-free chamber.



mutant that was disrupted in a gene that nobody knew anything about," says Ghirardi. "It was called a HydEF gene. It turns out that this gene product is responsible for assembling the catalytic structure of the hydrogenase. We found not only this gene, but another adjacent gene to it in the genome, and together they function to put together the metallic catalytic cluster in the hydrogenase.

"Now we can not only transform the E. coli with the hydrogenase gene, but also with the assembly genes. So E. coli makes the structural protein, but it's also able to make the catalytic cluster and assemble it into the hydrogenase."

NREL Scientist Paul King was the first to demonstrate the gene insertions into E. coli, a breakthrough that allowed the research team to conscript the E. coli bacterium to produce large amounts of hydrogenase, making it much easier to study. The researchers can mutate the hydrogenase genes, insert them into the E. coli, and see how they behave in terms of oxygen tolerance and hydrogen production.

"This has had a major impact in the field of hydrogenases and hydrogen production," Ghirardi says.

So far, Ghirardi's team has used the E. coli to examine the oxygen tolerance of a hydrogenase found in the Clostridium bacterium. King suspected that an unusual appendage on the Clostridium hydrogenase was the key to its oxygen tolerance. Lopping off the appendage, he inserted the truncated enzyme into E. coli. He hoped the altered enzyme would lack the oxygen tolerance, but such was not the case.

"We learned something from it," says Ghirardi, "but I wish the result had been the other way around."

The team is in the process of developing new methods to study oxygen tolerance in hydrogenases, using both random mutations and intentional ones. The work is being aided by a fruitful collaboration with computational scientists at NREL and at the Beckman Institute. These scientists are employing computer simulations to map possible pathways by which oxygen can access the catalytic site of the hydrogenase enzyme and inactivate it. By mutating the hydrogenase into a form that blocks those pathways, Ghirardi's team hopes to find the key to an oxygen-tolerant hydrogenase.

"Such mutations could allow us to engineer an organism that efficiently produces hydrogen through photosynthesis," says Ghirardi. "And once we fully understand the process, perhaps we can move beyond the organism, and create an entirely synthetic photochemical pathway for producing hydrogen from sunlight in vitro." ■

The Skystream 3.7 is a small wind turbine engineered to quietly and efficiently produce power from low-speed winds. The turbine was designed by Southwest Windpower with help from NREL.

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Award-Winning Wind Turbine Demonstrates a Successful NREL Collaboration

A cost-shared subcontract between NREL and Southwest Windpower has resulted in a small wind turbine that begins producing power at a lower wind speed than most wind turbines: only 7 miles per hour. The innovative Skystream 3.7 wind turbine earned a 2006 Best of What's New Award from Popular Science magazine and was recognized by Time Magazine as one of the "Best Inventions 2006." NREL started working with Southwest Windpower back in 2001, and the company took full advantage of the working relationship.

"They wanted to come out and pick our brains on a regular basis," says Project Leader Trudy Forsyth. "We were more closely involved with their design than we have been with anyone else. It was really rewarding for our technical staff, because they love to get into the technical details. And it was rewarding for Southwest Windpower, because they used NREL as their brain trust, which is a perfect role for us."

The 1.8-kilowatt wind turbine is quieter than most, drawing on acoustics research performed by NREL researcher Paul Migliore, who is now retired. That research called for a lower rotating speed and for blades with a blunt leading edge and a sharp, thin trailing edge. The turbine also employs NREL airfoils—developed by another NREL retiree, Jim Tangler—that are insensitive to roughness caused by dirt or bugs building up on the blades, and that yield a high energy capture for the turbine blades.

In addition, it draws on an idea conceived by Forsyth and NREL Engineer Ed Muljadi to use the turbine's generator to cause it to stall at high wind speeds. Combined with the turbine's downwind design, that approach simplifies the turbine, avoiding the need for a tail vane. NREL Project Leader Jim Green coordinated NREL's research support for the project.

David Calley, the president of Southwest Windpower, contributed another key innovation: the turbine uses a high-efficiency permanent magnet generator with a unique slotless stator. While most generators tend to stick or cog at a position where the rotating magnet aligns with one of the magnetic poles or slots in the stator, the slotless stator avoids cogging, allowing the generator to start turning at lower wind speeds.

Yet another innovation is the turbine's integrated electrical design. Southwest Windpower specifically designed the electrical characteristics of its generator to take advantage of the turbine's built-in power inverter, which delivers alternating current to the home. The electrical design avoids the energy losses that are common in such small wind turbines and delivers a higher system efficiency than most small wind turbines on the market.

The company is placing heavy emphasis on the "plug and play" characteristics of the Skystream turbine, which is designed for the suburban market. And to meet that market, the standard product offering is to mount the wind turbine on a 10-meter tower, which is a lower tower than many experts would consider ideal.

"For most of the United States, there are regulations that typically only allow you to put up about a 10-meter tower without getting zoning approval," says Forsyth. "Even though the wind resource is not ideal at that hub height, Southwest Windpower is banking on the fact that avoiding zoning approval will help them market and sell their turbine."

Forsyth also sees the company as having the ability to supply a large market with its turbine.

"They've been achieving high-volume wind turbine manufacturing for years—10 to 13 thousand per year—and they'll do that with the Skystream, as well," says Forsyth. ■